CARDIAC INTERFERENCE IN MYOGRAPHIC SIGNALS FROM DIFFERENT RESPIRATORY MUSCLES AND LEVELS OF ACTIVITY

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Abstract-**An interesting approach to study pulmonary diseases is the analysis of the respiratory muscle activity by means of electromyographic (EMG) and vibromyographic (VMG) signals. However, both signals are contaminated by cardiac activity reflected in electrocardiographic and cardiac pulse signals, respectively. Adaptive filtering and Singular Value Decomposition techniques were applied to reduce cardiac interference (CI) in signals recorded from three respiratory muscles (genioglossus, sternomastoid and diaphragm) in 19 subjects breathing against progressively increased negative pressure. The parameter Interference Relation (IR) is presented and its reduction with filtering is highly correlated with signal to noise ratio. This correlation indicates that IR is a good index to evaluate the level of interference. The CI is highest at low levels of ventilation when the respiratory muscles are less active. Furthermore, the level of interference depends on the selected muscle: the most affected muscle is the diaphragm, then sternomastoid, and finally genioglossus. This order is preserved for both EMG and VMG signals. That indicates similar level of CI for signals reflecting electrical and mechanical muscle activity. The reduction of CI by means of the presented filtering techniques is shown by the parameter IR especially in EMG signals.**
***Keywords* - Adaptive filtering, cardiac interference, electro-myograpy, singular value decomposition, vibromyography**

I. INTRODUCTION

Analysis of respiratory muscle activity and fatigue is a promising technique to evaluate pulmonary diseases. Muscle function depends on the level of ventilatory obstruction [1] and the presence of pathologies such as chronic obstructive pulmonary disease [2] or obstructive sleep apnea syndrome (OSAS) [3]. The electromyographic (EMG) and vibromyographic (VMG) signals are related to electrical and mechanical muscle activity, respectively. Time and frequency parameters calculated from these myographic signals indicate muscle activity and fatigue during normal and increased respiratory effort [2][4][5]. However, both signals are usually corrupted by cardiac activity reflected in electrocardiographic (ECG) and cardiac pulse (CP) signals, respectively. The reduction of these corrupting interferences is necessary in order to calculate parameters related directly to the respiratory muscle activity so that reliable results and conclusions are obtained. Power spectral density (PSD) functions of EMG and ECG as well as VMG and CP signals overlap in frequency (Fig. 1). Therefore, cardiac activity can not be removed by means of a linear and invariant filter.

II. MATERIALS

A. Subjects

Eight male patients with stable OSAS [age (yr.): 53.8±10.5; height (cm): 177±8.2; weight (kg): 96.4±19.2] and eleven male normal subjects [age (yr.): 41.7±4.3; height (cm): 176.9±6.1; weight (kg): 82.4±8.9] have been studied.

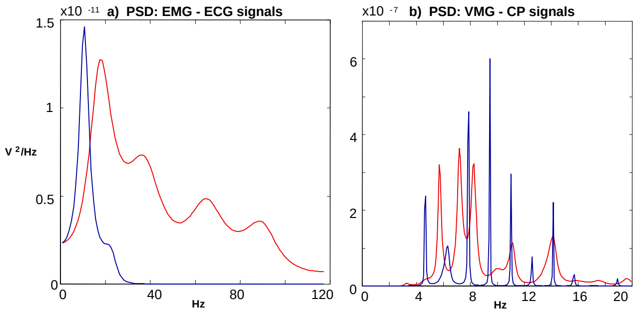

Fig. 1. Power Spectral Density functions of a) EMG (red), ECG (blue) and b) VMG (red), CP (blue) signals.

B. Signals and instrumentation

Four EMG and two VMG signals were simultaneously recorded from three respiratory muscles: genioglossus, sternomastoid and diaphragm. A surface EMG signal of genioglossus muscle was recorded with two electrodes (Ag-AgCl) placed on the submental zone (GEN-SEMG). In the same area, an accelerometer (Entran EGA-10) was also placed to record VMG signal (GEN-VMG). In addition, genioglossus activity was also monitored by means of intraoral surface electrodes located below the tongue (GEN-EMG) [6]. Two surface electrodes and another accelerometer were placed on the sternomastoid muscle to record EMG (SMM-SEMG) and VMG (SMM-VMG) signals, respectively. Finally, surface EMG signal was recorded from the diaphragm (DIA-SEMG).

The myographic signals were amplified and bandpass filtered using a multichannel analog amplifier. The selected bandwidths at -3 dB and the sampling frequencies were, respectively: 5-200 Hz, 500 Hz (VMG) and 5-400 Hz, 1000 Hz (EMG).

C. Increased respiratory effort

During the experiment subjects were in a supine position and breathed through a nose mask connected to a low-resistance respiratory nonrebreathing valve. The inspiratory port of the nonrebreathing valve was connected to the external source of a negative pressure.

The experimental protocol consisted of breathing without external pressure for 5 min before the negative pressure was applied. The pressure was decreased at 90-second intervals each time by the value of –7cm H_2O until the subject could no longer breath. The maximum pressure in absolute value reached by the subject was defined as maximum maintained pressure (MMP). For every subject, pressure in each step of the experiment was expressed as a

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percentage of the MMP, in order to normalize the data and to minimize possible influence of such factors like age and difference in physical condition.

Myographic signals corresponding to four respiratory cycles recorded when the subject breathed against a negative pressure of 85% MMP are shown in Fig. 2. Cardiac activity, with a periodicity of approximately 0.8 seconds, is observed in these signals.

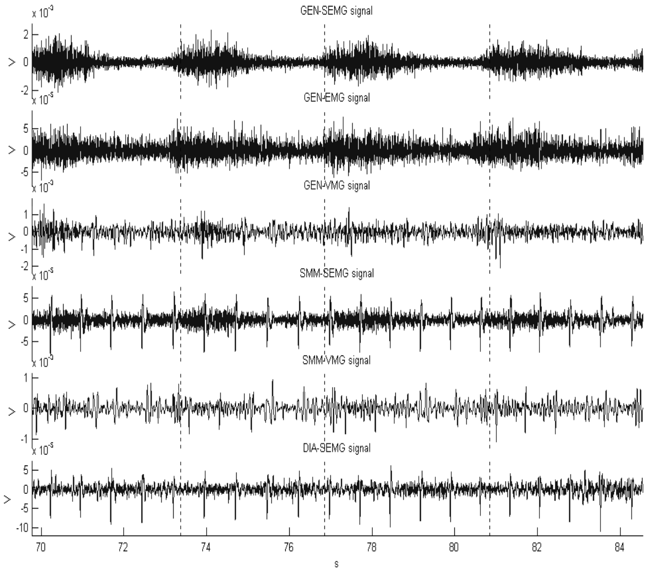

Fig. 2. Myographic signals recorded from a normal subject breathing against a negative pressure of –35 cm H_2O corresponding to 85% MMP. Vertical dotted lines separate respiratory cycles.

III. Methods

A. Adaptive filtering

Adaptive filters estimate a deterministic signal, myographic signal in our case, and remove the noise uncorrelated with it: the cardiac signal. The assumption that corrupted and corrupting signals are uncorrelated is valid because of different biological sources of the signals: muscle and heart, respectively.

In this study, an adaptive transversal filter is used and the weights are adjusted by means of a least mean square (LMS) algorithm [7]. Primary input, *d(k)*, is the recorded signal composed of EMG or VMG signal, *s(k)*, corrupted by noise, *n(k)*, that is ECG or CP signal, respectively. Filter output is expressed as follows [7],

$$y(k) = \sum_{i=0}^{L-1} w_i(k)\,x(k-i+1) \qquad (1)$$

where $w_i(k)$ are the L weights of the algorithm which are varying in every iteration i and $\boldsymbol{x}(k)$ is the vector with the last L samples of the reference signal. Algorithm tries to adjust the output filter to the noise signal. In this way, subtracting this output signal from the primary one we obtain an error signal, *e(k)*, that is the best approximation in least squares to the signal of interest *s(k)*. The weights are changed by a LMS algorithm every iteration minimizing the mean square value of the error estimation *e(k)* by means of the filter gain μ [7]:

$$\mathbf{w}(k+1) = \mathbf{w}(k) + 2\mu\, e(k)\mathbf{x}(k) \qquad (2)$$

The following characteristics of a specific adaptive filtering were found for its best performance reducing the cardiac activity by means of a simulation study [8]:

- Parameter L is the sample number of the beat with the shortest duration in the recording.
- A sequence of impulses synchronized with the QRS complexes is used as reference input.
- An optimal weight vector for the initial conditions is calculated to permit the algorithm to start working in steady state.
- A delay of 0.1 s between primary and reference inputs is considered.
- The parameter μ selected is $3\cdot10^{-3}$ and 10^{-2} in EMG and VMG signals, respectively.

B. Singular value decomposition

An *mxn* matrix **A** of rank q can be decomposed by means of the singular value decomposition (SVD) theorem that verifies the existence of the following parameters [9]:

- Real positive numbers $\sigma_1 \geq \sigma_2 \geq \ldots \geq \sigma_q \geq 0$, called singular values of **A**.
- *mxm* unitary matrix $\mathbf{U}=[u_1\ u_2\ \ldots\ u_m]$.
- *nxn* unitary matrix $\mathbf{V}=[v_1\ v_2\ \ldots\ v_n]$.

such that matrix **A** can be expressed as

$$\mathbf{A} = \mathbf{U}\,\Sigma\,\mathbf{V}^T = \sum_{i=1}^{q} \sigma_i u_i v_i^T \qquad (3)$$

SVD is applied to corrupted myographic signals using the near periodicity of cardiac activity which is different from the respiratory rate expressed in the muscle activity [10]. Recorded signal is distributed into the matrix **A** in row vectors corresponding to segments of every beat. Then SVD decomposes the matrix **A** with muscle and cardiac information in orthogonal components according to (3).

The most dominant mode, $\mathbf{Y}=\sigma_1 u_1 v_1^T$, corresponds with cardiac activity because of its nearly periodicity that has been used to create the initial matrix **A** [11]. This main mode is removed from the corrupted signal resulting in the filtered myographic signal.

C. Automatic detection algorithm of QRS complexes

An algorithm to detect automatically QRS complexes from the cardiac activity in EMG signals was implemented. In both filtering methods presented previously, the synchronization with this activity is needed.

In the algorithm, a matched filter with an impulse response of an average ECG beat was used in EMG signal. Another filter with an impulse response composed by the convolution of two average ECG beats was also considered. QRS complex instances were determined by means of a disjunction Boolean condition referred to the maximum outputs of both filters [10].

D. Interference parameter

A parameter related to the level of interference is defined and calculated from the autocorrelation function (ACF) of squared myographic signal:

$$r_{xx}[m] = \frac{1}{N}\sum_{n=0}^{N-1} x^2(n)x^2(n+m) \cdot \qquad (4)$$

The ACF has its absolute maximum at the lag m=0, $r_{xx}(0)$, and there are other local maximums in the lag corresponding to the periodicity of the signal. In corrupted myographic signals, the smallest periodicity is related to the cardiac activity because the respiratory rate is usually much longer, as we can see in Fig. 2. ACF of the SMM-SMEG signal presented in Fig. 2, normalized in respect to $r_{xx}(0)$, is shown in Fig. 3 where two parameters associated with interference relation (IR) are marked: IR_{max} is the local maximum around the mean beat duration (mbd±0.05s) and IR_{min} is the minimum of the ACF. Finally, the parameter IR is defined as the ratio between them: IR_{max}/IR_{min}.

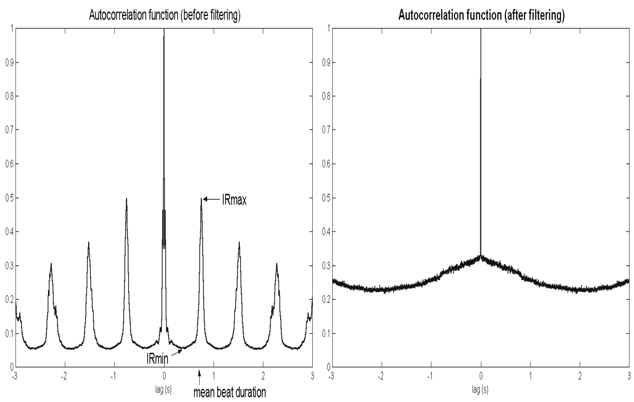

Fig. 3. Autocorrelation function of SMM-SEMG signal with cardiac noise and after filtering. Parameter IR is 9.01 and 1.05, respectively.

Theoretically, parameter IR would be unity without any interference. Because of the characteristics of myographic signals, small contribution from high frequency components in the ACF produces slightly higher than one value in spite of the lack of cardiac noise, IR_{max}>IR_{min}, as we can see in Fig. 3. Parameter ΔIR is also defined as:

$$\Delta \mathrm{IR} = 10 \cdot \log \frac{\mathrm{IR}_{\text{before filtering}}}{\mathrm{IR}_{\text{after filtering}}} \qquad (5)$$

This parameter indicates in dB the level of interference reduction in the recorded signal. Another parameter of interest is signal to noise ratio (SNR) calculated from the muscle and cardiac signals separated by the filtering.

IV. Results

The evolution of parameter IR, as a function of %MMP during the exercise in the corrupted myographic signals, is presented in Fig. 4. High levels of cardiac interference in diaphragm and sternomastoid muscle are shown by IR values. The adaptive filtering technique was applied to corrupted EMG and VMG signals. SVD method was also used in the latter signal for its best performance with medium and high levels of interference (SNR<5dB) [10]. In Fig. 5, filtered myographic signals corresponding to the same segments presented in Fig.2 are shown.

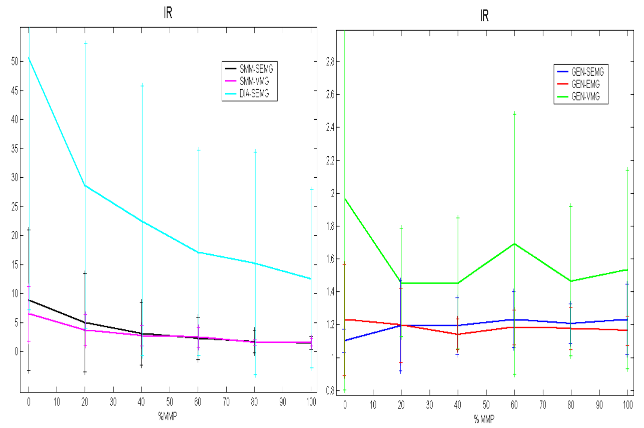

Fig. 4. Parameter IR as a function of %MMP during respiratory exercise in every corrupted myographic signal. Mean value and standard deviation of the population are shown.

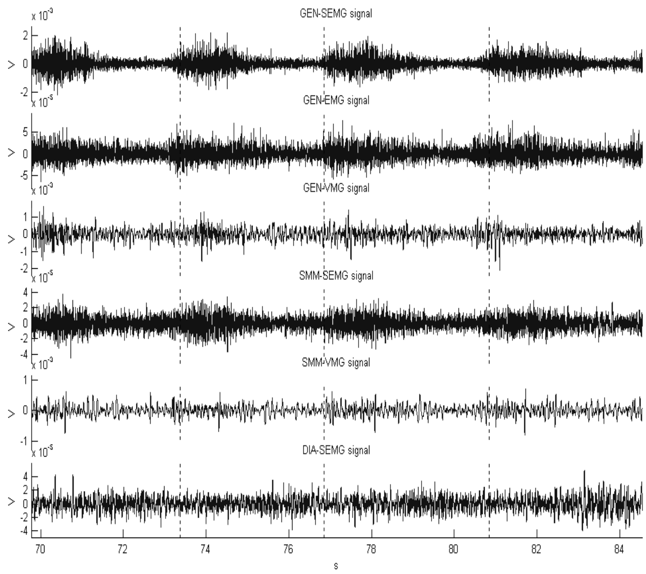

Fig. 5. Recordings of myographic signals presented in Fig. 2 after filtering process to reduce cardiac activity.

The results of filtering techniques by means of the IR in the filtered myographic signals are shown in Fig. 6. In EMG signals, mean values of IR are lower than 1.4 indicating the almost total absence of cardiac interference. The IR is not exactly one because of the high frequency components of ACF as we commented before. In VMG signals, IR is a little higher because their characteristics are similar to CP interference, but its reduction respect to IR before filtering (Fig. 2) is important.

The evolution of SNR during the exercise is shown in Fig. 7. An increase of this parameter with higher levels of applied pressure is found due to the increase of muscle activity. Level of cardiac interference can be separated depending on the selected muscle. The most affected muscle is the diaphragm with the lowest SNR. Then, sternomastoid and, finally, genioglossus muscles. This classification is obtained both in EMG and VMG signals.

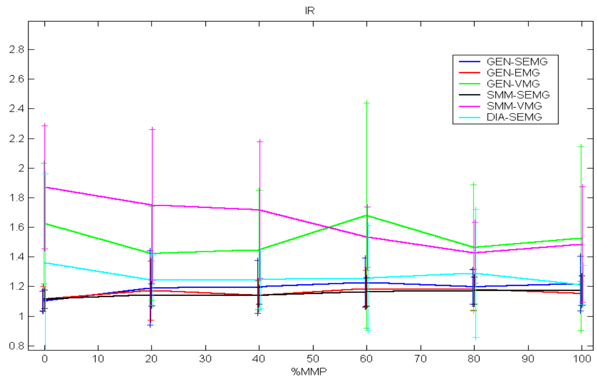

Fig. 6. Parameter IR as a function of %MMP during respiratory exercise in every filtered myographic signal. Mean value and standard deviation of the population are shown.

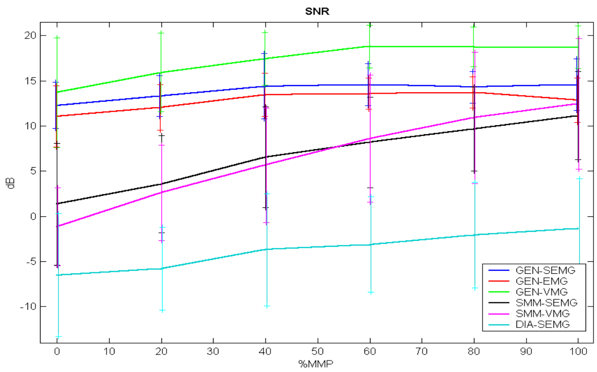

Fig. 7. SNR as a function of %MMP during respiratory exercise in every myographic signal. Mean value and standard deviation of the population are shown.

Parameter ΔIR was calculated and its mean value of the population was found highly correlated with the mean value of SNR during the exercise: correlation coefficients in all the signals, except GEN-SEMG with almost absence of interference, are higher than 0.93 in absolute value. This high correlation indicates that parameter IR is a good index to evaluate the level of interference.

V. Conclusion

Two methods designed to reduce cardiac interference in myographic signals are presented: adaptive filtering with LMS algorithm and SVD. Both techniques were applied to the signals recorded from three respiratory muscles (genioglossus, sternomastoid, and diaphragm) during an incremental respiratory effort exercise. Parameter Interference Relation (IR) calculated from the ACF of squared myographic signal was also presented. Reduction in the value of IR with filtering was highly correlated with SNR. This correlation indicates that IR is a good index to evaluate the level of interference.

Cardiac interference was higher at lower levels of ventilation when the respiratory muscles were less active. Cardiac activity affected most significantly signals recorded from the diaphragm, then sternomastoid, and finally genioglossus muscles. This classification, true for both EMG and VMG signals, indicates that cardiac activity interferes similarly with indicators of electrical and mechanical muscle activity. The reduction of cardiac interference by means of the presented filtering techniques, especially effective in EMG signals, was reflected by the parameter IR.

Finally, the necessity of filtering cardiac interference prior to the evaluation of respiratory muscles activity has been demonstrated and two filtering techniques applied to the signals from different respiratory muscles have been presented, applied and validated.

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